Comparison of Flow Patterns of Different Stent within a Simulated Disease Model

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Background information

Cardiovascular disease is gaining increasing traction and concern among Singaporeans. A preliminary study to investigate effectiveness of Percutaneous Coronary Intervention (PCI) [1]; a total of 7544 patient data was taken into the study, with 684 of these patients experiencing major adverse cardiovascular event (MACE) such as death, revascularisation or myocardial infection within 6 months. Although MACE rate stands at 9% in the previous study, this rate is set to increase as Singapore reaches the silver tsunami. An even older study quoted the complication rate of patients after vascular angioplasty was higher than those who have undergone balloon angioplasty [2]. Although the rate of complication is relatively small (5.9% vs 3.2%), what is certain that the number of patients is set to increase due to changing of dietary habits and lifestyles over time.

Previous data from National Heart Centre Singapore have highlighted signs of this trend, with a consistently increasing number of PCI procedures from the year 2007-2012 [3]. Although a decrease is observed in post 2012 years, it is unlikely the trend can sustain as demand for such services grows as the population ages.

A secondary survey conducted within the period of 1st October 2015 to 30th September 2016, an average of 189.2 patients were admitted to each of the 9 hospitals involved, with an additional 699 patients who had undergone a day procedure for angioplasty [4]. A conservative estimate of 2270 patients would have undergone angioplasty within the same period, as well as an estimate of 932 patients would have undergone day surgery procedures. This further highlights the increased demand for coronary angioplasty surgery, along with increased MACE possibility among patients.

Numerous studies have tried differing methods to determine the successfulness of a stent. Pierce at al [5] determined the effectiveness of implanted stent by subjecting patients to a MRI scan to determine the degree of carotid stenosis by looking at resultant velocities, location of carotid bifurcation, distal extent of plaque and diameter, presence of redundancy of internal carotid artery. Their results concluded that carotid arteries are elevated among with patients with closed cell stents compared to those who have open-celled stents. The paper also raised up the problem of using the velocity boundary condition if stents require restenosis might be premature.

Chiastra at al performed a fluid-structure interaction (FSI) for a coronary artery by varying the stent material (bare metal vs drug eluting) used in each scenario to study effects of wall compliance on hemodynamic quantities [6]. However, due to the nature of the programme and study, stent material may not make a significant difference in results; with the study showing the difference of percentage area of low TAWSS between rigid wall cases (1.5%) and drug eluting stents at 1.0% [6]. The other limitation discussed by the study is the use of idealised vessel geometries to determine wall shear stress (WSS) introduced by each stent.

The aim of this paper is to perform a CFD study to compare the performance of 3 different stents under the various geometrical, velocity and pressure condition. The WSS among the 3 stents were studied and compared to simulate its performance over time.

Methodology - Stent selection

Studies by Pierce at all; identified 6 stents among their sample group, with Xact Carotid stent (Abbott Vascular, Santa Clara, California), Nexstent Carotid stent, Carotid Wallstent (Boston Scientific, Natick, Massachusetts) being classified as closed-cell stent and Precise carotid stent, Protégé carotid stent (Cordis, Warren, New Jersey), Acculink carotid stent (Acculink system, Santa Clara, California) as open-cell stent. Nexstent was chosen as it has the largest free cell area (4.7mm^2) [5] among classified closed-cell stents. XactStent was also selected as it is structurally like other stents quoted in other studies [6]. The Nexstent and XactStent in comparison have the closest cell surface area difference compared to the other combination of stents.

A reference stent (Palmaz- Schatz stent model inspired, denoted as simple stent) is also included in this study to provide a reference to velocity and pressure performance. All stents were assumed to be of the same material for better comparison.

To investigate the effect of boundary conditions on the flow pattern in the vessel, three stents were placed in a straight tube and a curved tube entrance model. Subsequently, both healthy and diseased waveforms were implemented as boundary conditions so their effects can be evaluated.

Method

Instead of modelling the entire vessel wall and stent, a 45-degree portion of the stented vessel would be modelled instead, seen in figures 3-5 Literature review from [7] where studies on the impact of bifurcation angle were studied suggested that varying diameter of vessel could have varying effects on flow, hence the decision was made to set the vessel radius at 1.57mm, A small gap of 0.08mm was formulated between stent and vessel to avoid convergence issue. The effect of this small gap on the overall flow pattern was negligible since it was less than 5% of overall vessel radius. The stent is positioned at the middle of vessel with 3mm off from the vessel inlet and outlet. After an initial simulation was run, the same boundary conditions were run through a curved entrance geometry containing the stent. For the curved entrance geometry, a 180-degree slice was taken which encompassed the curved entrance and half of the stent, seen in figures 6-8.

Since this is a numerical flow study, velocity and pressure waveforms defined by Davies et al [8] have been set as the healthy waveform and experimental values from patients obtained by Obata et al [9] was set as diseased waveform.

Fourier transform in the MATLAB was then used to perform curve fitting for the 4 functions, set at a minimum 98% accuracy rate. The equivalent functions are provided below:

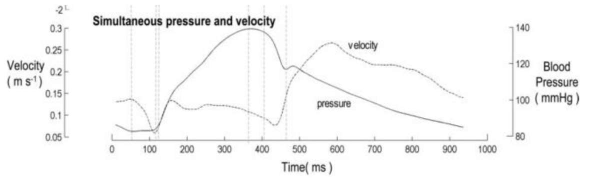

Figure 1 Waveform for healthy pressure and velocity, [8]

The healthy waveform runs for 1 second.

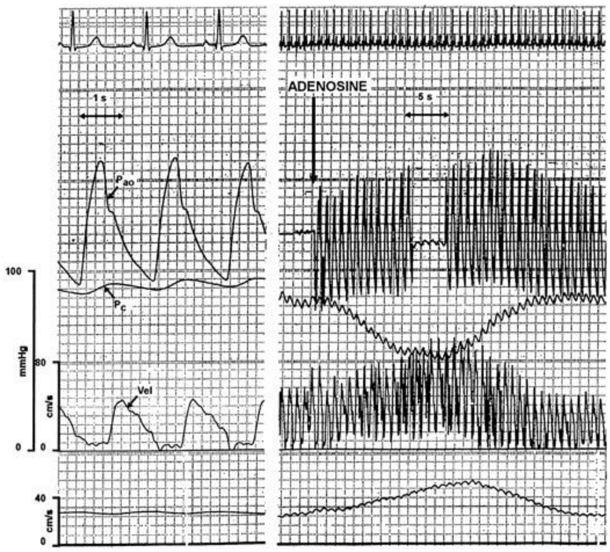

Figure 2 Waveform for diseased velocity and pressure [9]

The diseased model waveform runs for 1.69s.

In addition to the pressure and velocity waveform set, the flow is assumed to be non-Newtonian Carreau model as suggested in another paper in the study of aortic aneurysm [10]. The following parameters are observed:

$$\eta_0 = 5.6E^{-2} kg/m \cdot s$$

$$\eta_\infty = 3.45E^{-3} kg/m \cdot s$$

$$n = 0.3568$$

$$\lambda_C = 3.313s$$

Carreau Model formula [11]:

$$\eta_a = \eta_\infty + \frac{\eta_0 - \eta_\infty}{[1 + (\lambda_c \dot{\gamma})^2]^N}$$

Where η_a is the derived apparent viscosity.

With these parameters set, the stent was placed in a straight tube geometry and subsequently in a curved entrance geometry. For each geometry, a healthy model and diseased model was simulated

Figure 3: Simple Stent in straight tube geometry

Figure 4: NexStent in straight tube geometry

Figure 5: XactStent in straight tube geometry

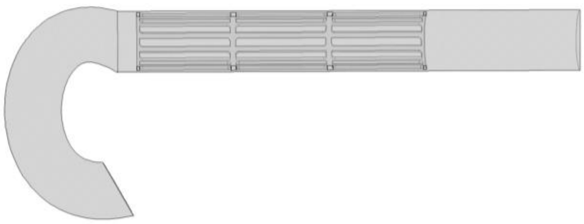

Figure 6: Simple Stent in curved entrance geometry

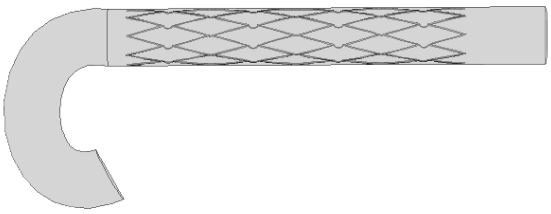

Figure 7: NexStent in curved entrance geometry

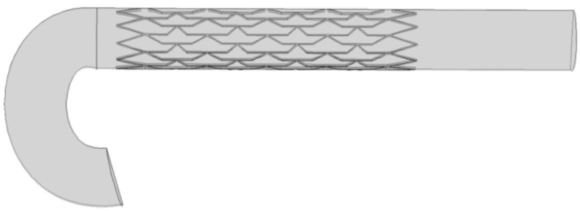

Figure 8: XacStent in curved entrance geometry

Preliminary results

We first begin this section by examining the healthy and diseased waveform model. Velocity and WSS were taken at early systole, mid-systole, late systole and diastole for healthy and diseased model performance in each geometry(. As observed in figures 1 and 2, the velocity range for the 2 models are quite similar, with the diseased waveform model of range 0 ~ 50cm/s and healthy range of 0-30cm/s. however, pressure range for diseased model is 90-160 mmHg, compared to the healthy range of 80-140mmHg within a cardiac cycle. A comparison of control vessel performance is provided in the following figures below:

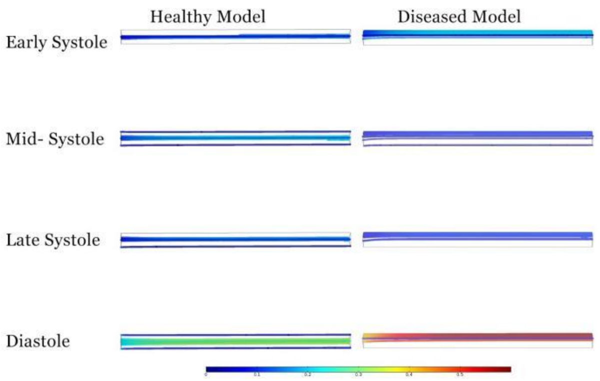

Figure 9: Velocity Comparison Chart of straight tube vessel of Healthy and Diseased Model

Figure 9 shows a comparison chart between early, middle, and late systole and diastole velocity flow in the control vessel of healthy and diseased model respectively.

The healthy model velocity shows a consistent range of 0-0.3m/s for the entire cardiac cycle, quite close to the given velocity profile in figure 1. The diseased model velocity (right) shows relatively low velocities (0-0.2m/s) in the systole range and high velocity (0.5-0.6m/s) in the diastole range.

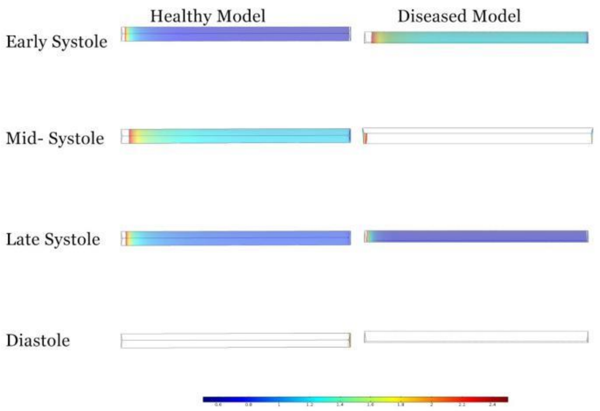

Figure 10:WSS comparison of straight tube vessel of Healthy and Diseased Model

Figure 10 shows a comparison of WSS performance between the healthy and diseased model waveforms. In the diseased model, the derived WSS value did not follow the trends observed in the healthy model. Although in figure 9 the velocity of the diseased waveform in mid-systole and late systole were largely similar, we see that in figure 10 that the derived performance shows 2 extremes with one ranged above 2.5Pa (mid systole) and one near the lower limit of 0.5Pa (late systole), which have been identified as a range for "safe WSS" values, as WSS>2.5Pa can trigger plaque rupture, with subsequent thrombosis and rupture. WSS<0.5Pa is thought will trigger atherosclerosis, which will be evaluated in figure 11 below: [12].

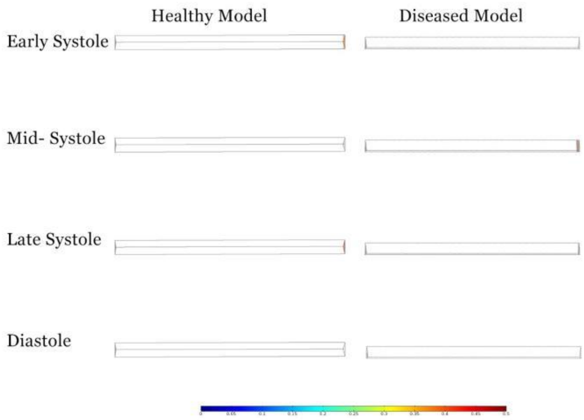

Figure 11: Low WSS comparison of straight tube vessel of Healthy and Diseased Model

No low WSS zone are found in Figure 11 at the 4 time points given. Since the control vessel is modelled as a straight tube geometry, such performance is expected.

The function of the control vessel is to provide a benchmark of stent performance by comparing it with no stent in the vessel to give a reference level to performance expected.

Having completed the preliminary comparison, we now examine the hemodynamic performance of each of the stents in a straight tube geometry before moving into the curved entrance vessels.

Performance Differences in Straight Tube Geometry

The performance of the simple stent under 2 different waveforms were first examined, proceeded by the open cell stent(XactStent) and subsequently the closed cell stent(NexStent).

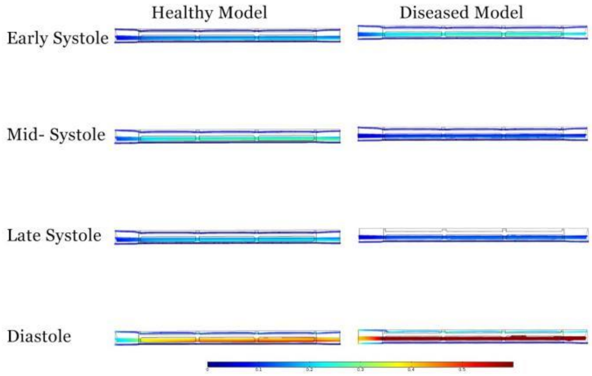

Figure 12: Velocity comparison of simple stent in straight tube vessels in Healthy and Diseased Model

In the simple stent tests, the resultant flow rate for both models are faster compared to the control vessel trials. We can attribute this to the structure of the stent, which has remained constant in both scenarios. Another observation is the visualisation of streamlines close to the wall of stent, which are constantly visualised as being slower than the other streamlines closer to the middle section.

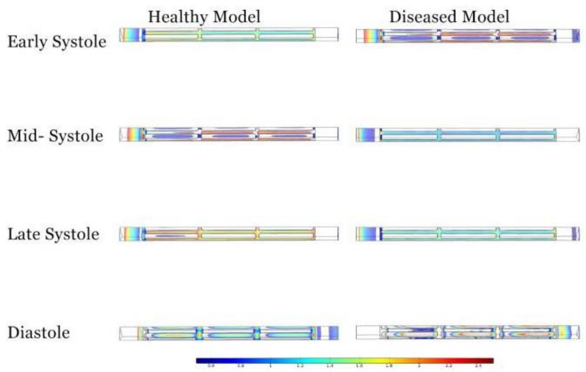

Figure 13: WSS comparison of simple stent in straight tube vessels in Healthy and Diseased Model

In figure 13, the performance of the stent in the healthy waveform is close to the control model, as predicted by the control WSS in figure 10. However, the disease model at mid-systole showed a significant decrease in WSS values from the control, whereas an increase of WSS range was observed at late systole. The period of mid-systole to late systole coincided with a significant drop in pressure in the diseased model, which responded quickly in the control vessel. The change of distribution of WSS can be attribute to the boundary layer effect along the vessel. Given that shear stress is related to velocity gradient [13], larger velocity gradients would co relate to larger wall shear stress values. In figure 12-14, a stent section was added within the walls of the vessel, which acted as a secondary boundary later. The flow trapped between the vessel and stent struts would have a predominately low flow due to restricted space in between, inducing low wall shear stress.

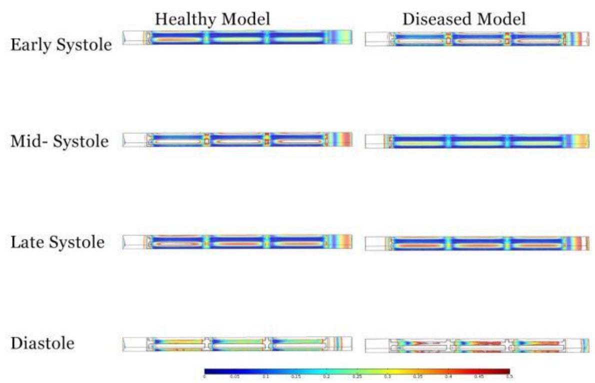

Figure 14: Low WSS comparison of simple stent in straight tube vessels in Healthy and Diseased Model

As discussed in figure 12 and 13, the boundary layer along the vessel induced low WSS along the edges of the stent. In this case, the stent struts are parallel to the flow direction, which incidentally separated the flow out and reduces its intensity. This would also explain the presence of low WSS along the walls of stent, which increases the chances of plaque deposition along stent walls.

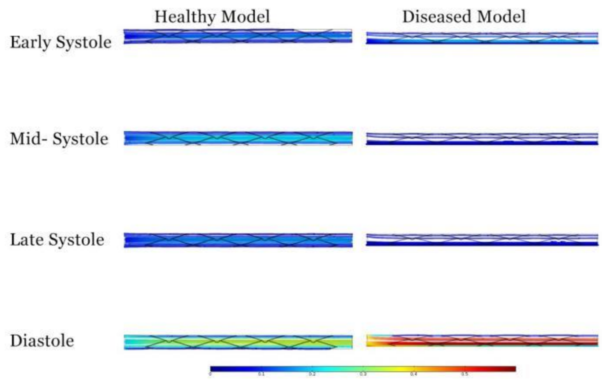

Figure 15: Velocity comparison of XactStent in a straight tube vessel in Healthy and Diseased Model

In the XactStent tests, the resultant flow pattern is quite close to the values derived in the control vessel trials (figure 9), with no induced flow acceleration.

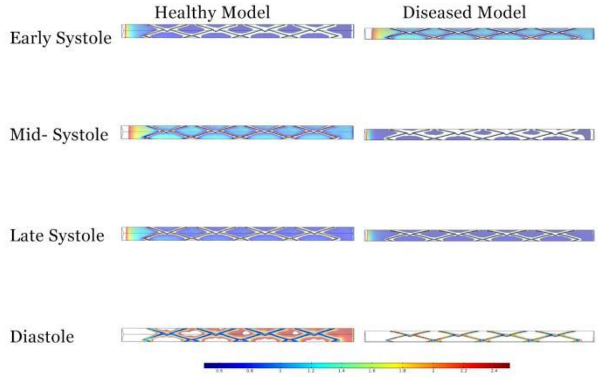

Figure 16: WSS comparison of XactStent in a straight tube vessel in Healthy and Diseased Model

The diseased model shows a higher WSS range in than early systole in the early systole. By mid-systole, the healthy model shows a higher WSS than the diseased model, which has an increase in low WSS area. By late systole, both models are seen to have the same WSS range, which changes again in the diastole, with the diseased model having a shear stress range above the healthy model in the same time.

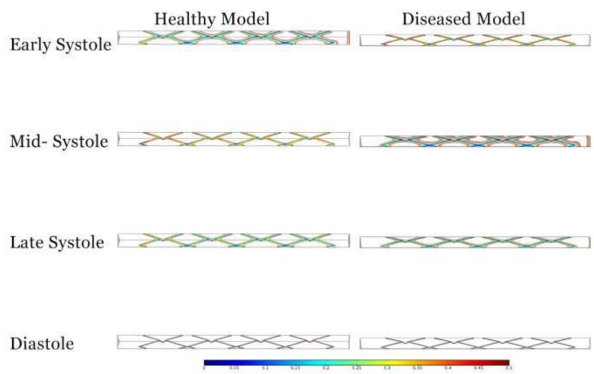

Figure 17: Low WSS areas comparison of XactStent in a straight tube vessel in Healthy and Diseased Model

Prominent areas of Low WSS are observed in early systole of the healthy model, Mid systole in the diseased models and relatively equal areas in both models in the Late systole stage. There was reduced are of Low WSS found in the diastole.

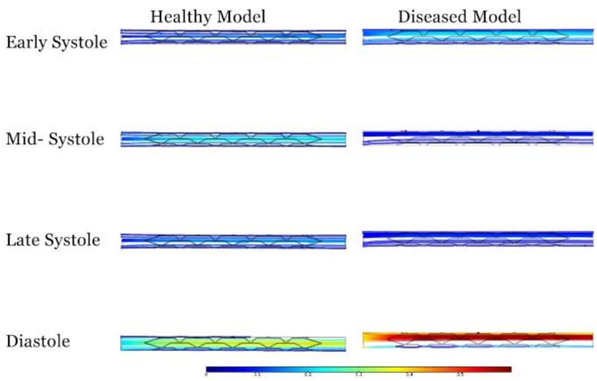

Figure 18: Velocity comparison of NexStent in a straight tube vessel in Healthy and Diseased Model

In the Nexstent model, there are projections of streamlines along the walls of the stent, like those set by the simple stent model. However, the resultant streamlines are quite close to the control vessel tests.

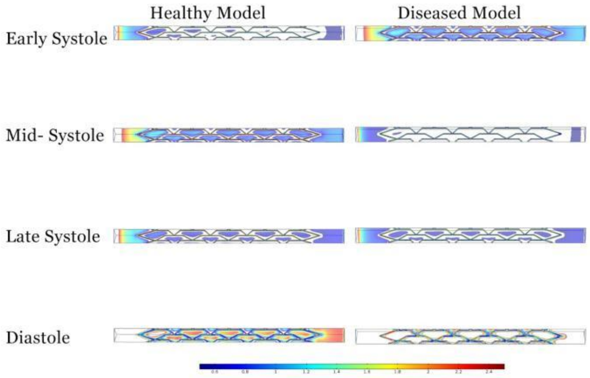

Figure 19: WSS area comparison of NexStent in a straight tube vessel in Healthy and Diseased Model

The healthy model in early systole shows a generally lower WSS range compared to the same model in the diseased model. By mid-systole, the WSS range in the diseased model range is recorded to be lower than that of the healthy model. In late systole, the 2 models are observed to have the same WSS range. In the diastole stage, the healthy model has a large area towards the upper range of the “safe WSS range”, but the diseased model would be in the recirculation zone, with the stent areas in the “safe WSS range”.

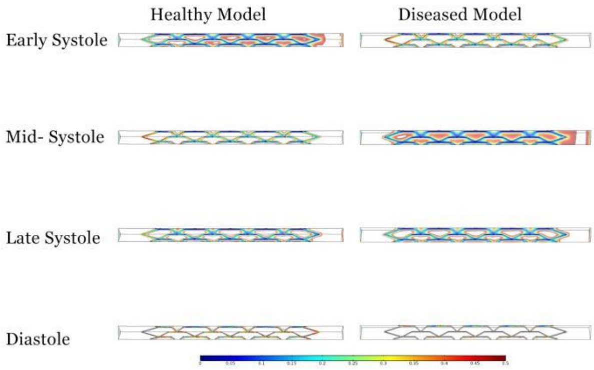

Figure 20: Low WSS area comparison of NexStent in a straight tube vessel in Healthy and Diseased Model

As expected from figure 19, prominent areas of Low WSS in early systole of the healthy model, Mid systole in the diseased models and equal areas in both models in the Late systole stage. There was reduced area of low WSS found in the diastole.

Results analysis

Having identified various areas and time points that are prone to low WSS formation, we would now examine the cross section of flow and corresponding WSS values to possibly explain its formation in a curved entrance vessel.

A study of vessel cross section was performed in the curved entrance vessel. 3 cross sections were taken at 1mm, 6mm and 11mm from the stent entrance, at the 4 time points in the model cycle for both the diseased and healthy model (50ms, 280ms, 520ms, 930ms and 110ms, 200ms, 410ms and 500ms). The slices were placed with distance of 5mm in between each other to get a comprehensive picture at the distal and proximal ends of the stent. The following figures show calculated WSS in the cross section and corresponding contour lines that reflect the overall flow pattern at the cross section.

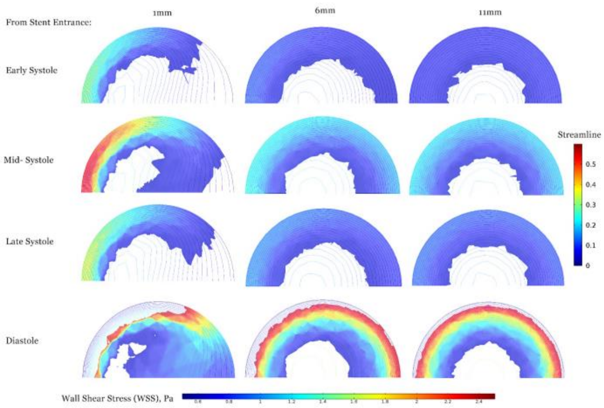

Figure 21: Cross sectional study of Healthy Model in curved entrance Control Vessel

We begin by examining the cross-sectional study of a healthy model in a curved entrance control vessel. The first observation would be the central flow skews to one side at 1mm distance from stent that slowly moves back to the centre at the 6mm and 11mm cross section. As examined previously, the inclusion of a curved entrance before the stent change the flow pattern before passing through the stent. At 1mm cross section, the smooth flow pattern is shifting from the entrance curvature to the centre of the stent, following the laws of thermodynamics.

The second observation would be observed lower WSS values towards the centre of the flow although the overall velocity flow rate is higher towards it. This defies the convention set in the earlier section where higher velocity is usually associated with higher WSS values. It has been explored in Miller’s text that Shear stress is a component of velocity rate and its gradient [13]. Although the centre of the stent has visibly faster flow than its sides, the gradient in this instance is much slower as the speed remains relatively constant and is only reflected to the changes in the input velocity. this would explain the centre of the flow having recorded the highest flow rate but lowest shear stress.

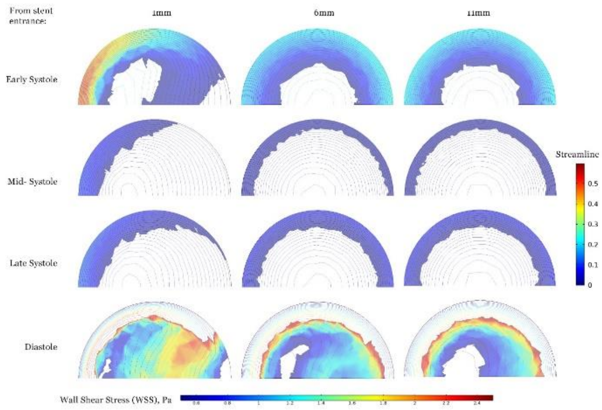

Figure 22: Cross sectional study of Diseased Model in Curved Entrance control vessel

The diseased model cross section has a very similar mid-systole and late systole due to the overlapping velocities at the 2 points in waveform. In the diastole, there is a sustained area of WSS at 2 Pa(orange) at the 1mm cross section, which might be recirculation zone. As the cross section moves towards 6mm and 11mm, the zone reduces in WSS values and eventually moves towards the centre of the flow

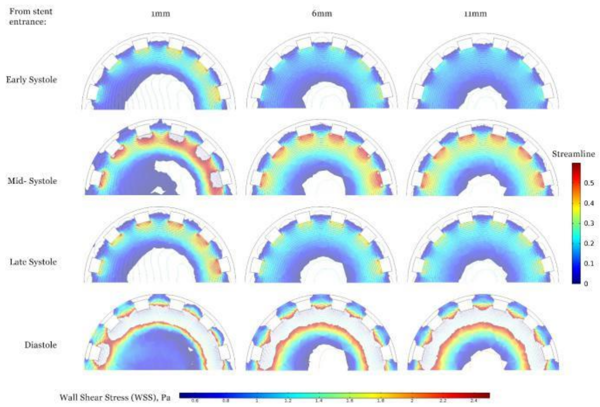

Figure 23: Cross sectional study of Simple Stent in curved entrance vessel with a healthy model

In a study of healthy model with a simple stent, the stent walls in this case play a role in altering the WSS formation. Comparing to the control vessel, there is a noticeably larger WSS generate along the walls of the strut constantly in the throughout the waveform, with a consistent deposition zone along the vessel walls that starts about halfway through the depth of the struts. The zones of high wall shear stress along the struts correspond to the high velocity gradient that the flow moves through due to the speed difference between the flow centre and the stent (0m/s).

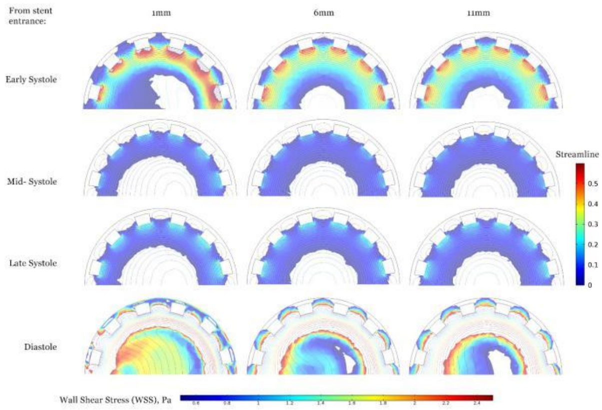

Figure 24: Cross sectional study of Simple Stent in curved entrance vessel in a diseased model

The problem is more pronounced in the diseased model. For instance, the low velocity in the mid-systole and late-systole in the waveform creates extensively large deposition zones, with most of the WSS calculate in a higher range than the levels set by the control test.

The subsequent figures we would examine the effects of a smaller strut walls on flow and the comparison of performance between and open cell stent and closed cell one.

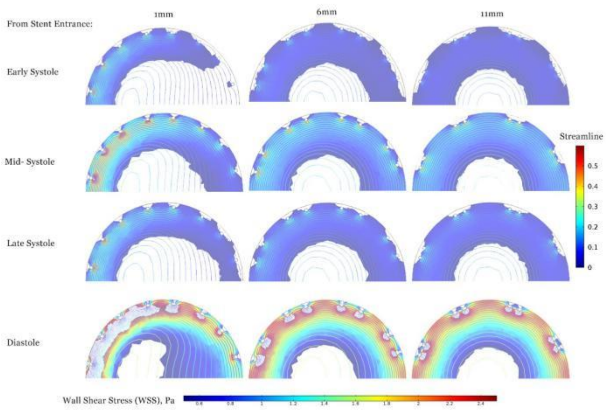

Figure 25: Cross sectional study of XactStent in curved entrance vessel with a healthy model

In the study test of XactStent with the healthy model, most of the WSS level set by the control values are maintained throughout the waveform. Except for areas of vessel wall covered by stent struts, most of the cross section lies within acceptable range of WSS. In this case, the shear stress has been reduced as the flow needs to overcome a smaller area of stent wall, which results in smaller areas having a large velocity gradient.

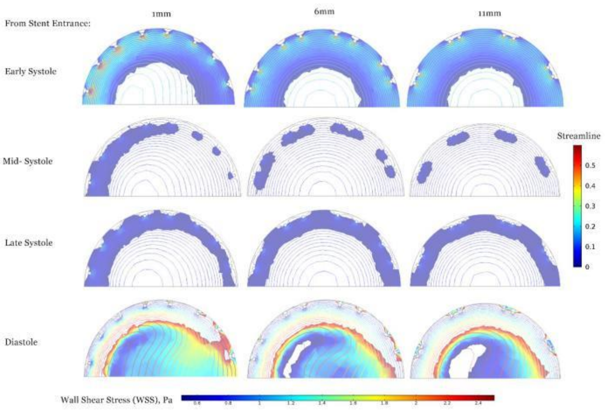

Figure 26: Cross sectional study of XactStent in curved entrance vessel with a diseased model

Similarly, in the diseased model test, the stent produces a WSS quite like the disease model, except that the areas of low WSS have extended quite considerably in the mid systole time point.

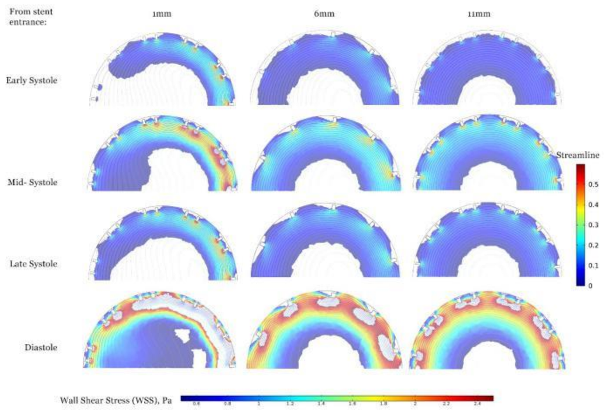

Figure 27: Cross sectional study of NexStent in curved entrance vessel with a healthy model

In the study of Nexstent with a healthy waveform, the effect of wall stationary wall struts is more pronounced than in the Xact test with healthy model. Although the parameters for both tests remain the same, the geometry of the stent might redirect the flow which results in this change. The "notch" observed at the 6mm cross section might be a result of the slanted stent structure, with the high velocity gradient shifting to accommodate the position of the new stent struts along the cross section.

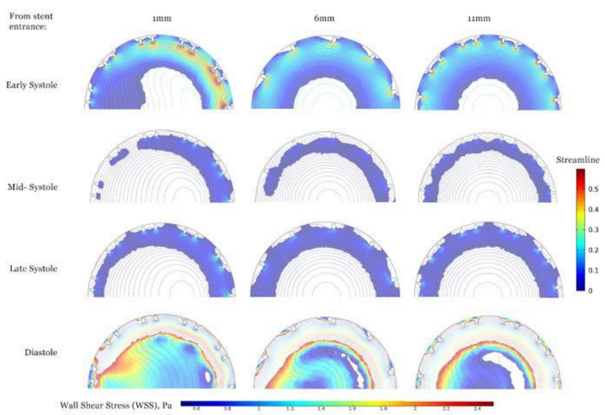

Figure 28: Cross sectional study of NexStent in curved entrance vessel with a diseased model

In the disease model, the Nexstent generates a WSS that is also quite close to the ones set by the control, compared to the test performed on the healthy model.

Further recommendations

In this study, it has been highlighted how the shape of the strut, the size and its arrangement affects the effectiveness of coronary stent treatment. From this study, an ideal stent would have minimal strut thickness and rounded edges to prevent vessel wall deposition and unnecessary shear stress on strut surfaces. Although the open cell stent model in this case had generated the closest WSS values set by the control, further testing needs to be done to determine if the same applies for all open-cell stents.

Another area of expansion would be fitting the stent into a curved vessel model and to examine its effects on velocity, WSS and areas of low WSS before moving into testing patient specific coronary vessels with stents. Alternatively, the same tests can be performed for different stents but using the same geometry to examine the hemodynamic performance.

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